DEVELOPMENT AND APPLICATION OF SPACE INFLATABLE STRUCTURES

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Abstract

Space inflatable structures technology continues to make progress in the past two years. Additional applications to future space missions have also been proposed. However, much still remains to be done to develop this high-payoff technology to a high degree of mission-readiness. This paper presents an overview of this technology with an emphasis on its recent development and applications.

1. Introduction

Space inflatable structures technology is one of the emerging technologies that can potentially revolutionize the design of large space structural systems. Many of the future NASA missions will need space inflatable structures to achieve their launch volume and mass goals. This is especially true for missions that employ flight hardware components and systems of relatively large in-orbit configurations. These include radar antennas, solar arrays, sunshades, solar concentrators, and telescope reflectors. At present, these hardware components and systems commonly use mechanically deployed structures to meet their launch volume constraints. Compared to mechanically deployable structures, space inflatable structures have several distinct advantages, such as much lighter weight, higher packaging efficiency, lower life-cycle costs, simpler design with fewer parts, and higher deployment reliability. It is envisioned that inflatable structures will replace mechanically deployed structures for many future space applications.

Depending on its configuration accuracy requirements, a space inflatable structure may fall into one of two roughly defined groups: hi-precision and low-precision. At this time, hi-precision inflatable structures refer mainly to large telescope reflectors that operate in the near-infrared and visible wavelengths. These reflectors require reflective surfaces with extremely small configuration errors, usually in the micron and sub-micron ranges. Before these hi-precision reflectors can be actually used for space missions, major technology advancement must occur. These include breakthroughs in high-quality thin films, reflective coatings, hi-precision manufacturing, assembly and measurement, and active in-orbit configuration control. On the other hand, the low-precision inflatable structures, which are mainly for the applications of radar arrays, solar arrays, sunshield, and radio-frequency reflectors, are relatively more ready for near-term and mid-term mission applications.

The major technology development needs of low-precision inflatable structures are inflation deployment control and stability, space rigidization, modeling and analysis tools, materials data and space survivability. In the past several years, researchers in this field have been addressing these technology needs. Many of the research results have also been successfully demonstrated in ground testing of engineering models. A review of some of these efforts is previously given in [1].

2. Current Applications

Low-precision inflatable structures cover a very wide range of structural systems that are constructed with long, tubular elements, such as
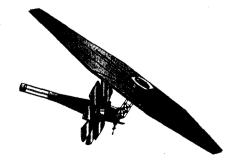

Figure 1. NGST Reference Architecture

Figure 2. A 1/2-scaled NGST Inflatable
Sunshield Engineering Model

beams, columns, planar frames, and space trusses. These inflatable structures are commonly used to deploy, support and tension thin-film membranes. Currently, hardware design of several selected low-precision space inflatable structural systems is rapidly maturing. These include the inflatable sunshield for the Next Generation Space Telescope (see Figures 1 and 2), the inflatable synthetic-aperture (SAR) radar antenna (see Figures 3 and 4), and various inflatable solar array designs. Development details of the first two systems can be found in several published papers [2 through 6].

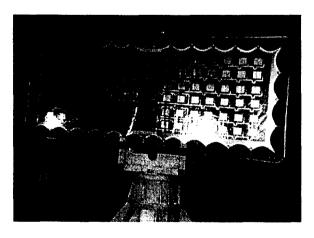Figure 3. Inflatable Rolled-Up SAR Antenna Array
(Stowed Configuration)

Figure 4. Inflatable Rolled-Up SAR Antenna Array
(RF Testing)

3. Stability and Control of Deployment

For long and highly flexible tubular structures, unstable free inflation deployment could be very volatile. This was clearly evidenced by the in-orbit deployment of the Inflatable Antenna Experiment (IAE) flown in May 1996 [7]. For free deployment of a long flexible boom, regardless of whether it is rolled up or z-folded before deployment, stability can be achieved only when the leading portion of the boom has sufficient momentum through the entire deployment process. This requirement was recognized by the IAE designers – but was not met during the flight due to the unexpected effects of residual air pressure in the thin-film canopy [8].

After the IAE space experiment, research effort started to focus on controlling inflation deployment by proactive means. This was achieved mainly by providing externally applied resistive force to balance the inflation pressure. One of the early concepts uses collapsible diaphragms to divide a long inflatable tube into a series of sectional compartments to achieve a "sequential" inflation process, which is controlled and relatively stable [9]. A second concept, also described in [9], suggests the use of constant-force coil springs that are embedded in the tube walls. A stable deployment of the tube is achieved by balancing the inflation pressure and the restoring forces of the springs.

Based on the finding that controllability and stability of inflation-deploying structures can be achieved by providing resistive forces to balance the inflation pressure, many innovative design concepts have emerged in the past three years. For example, the embedded coil springs can be replaced by Velcro® strips glued to the outside of the tube wall of rolled-up booms. Velcro® strips are easier to install and offer two additional advantages over embedded springs. First, booms with Velcro® strips can be packaged in both rolled-up and z-folded configurations. Secondly, the Velcro® strips will not impose any returning forces on the deployed tube when the inflation deployment is completed. It is worth mentioning that Velcro® strips also have had space flight heritage. In the Mars Pathfinder mission, Velcro® strips were successfully employed to slow down the deployment of the landing ramps for the rover. Another early example of deployment control design, proposed and developed by the researchers at L'Garde, involves the use of a mandrel. During the deployment process, the

inflating tube is forced to go over an internal guiding mandrel and develop frictional forces to balance the inflation pressure. The application of this mandrel-guided approach to control the inflation deployment of a space rigidizable truss has been successfully demonstrated by L'Garde. More recently, a wire brake design was developed by ILC-Dover. This design is currently being refined for the application to an inflatable sunshield space experiment (the ISIS) scheduled to be flown in the Space Shuttle in 2001.

4. Space Rigidization

A space inflatable structure derives stiffness from the tensioning of its flexible walls by inflation pressure. In space, small holes will be created in the tube walls by impacts of micrometeoroids and space debris. This leads to leakage of internal pressure and loss of structural integrity. Two options are available to remedy this situation: (1) to provide sufficient make-up gas, or (2) to rigidize the structure after deployment. The first option is only feasible for applications that will last for a very short time. For most space missions that have a relatively long mission life, rigidization of inflatable structures is necessary and many researchers have engaged in finding the best rigidization method. A summary report on the early efforts was given by Schwartz [10], who also pointed out the advantages of several pioneering methods involving solvent loss systems. In a solvent loss system, a volatile plasticizer leaves the impregnated fabric that form the walls of an inflatable tube when deployed in space vacuum. One of the solvent loss systems, which uses a water-gelatin solution, was first suggested in 1966 by Keller et al. [11] and later successfully applied by L'Garde to an inflatable/rigidizable space truss [12].

Many of the on-going research efforts focus on rigidization techniques that use cueing resins. Various polymer resins have been considered. These include resins that are curable by heat, cold, ultra-violet, and infrared. At this time, researchers in the industry continue to refine and improve space curable resins and their application processes. Example development efforts include heat-cured composites (thermoplastic and thermoset) at ILC-Dover, cold rigidization at L'Garde, and UV-cured composites at Adherent Technologies [13].

In addition to the solvent-losing and resin-curing approaches, another space rigidization method, known as the stretched aluminum laminate method, is also receiving much attention. In 1984, Hinson and Keafer [14] described the self-rigidization process of stretched aluminum laminate. These sandwich laminates are constructed by bonding aluminum foils to polyester films, such as Kapton. While the polyester films provide tear resistance and a gas seal, the aluminum foils are stretched by pressure just above the yield point to provide rigidity of the inflatable structure. In addition to taking advantage of the inflation system that is already needed for deployment, this method also offers the following distinct advantages: (1) It can accommodate inflatable tubes that are either rolled up or z-folded; (2) It does not require power; (3) It has negligible level of outgassing and (4) Its rigidization is reversible for repeated ground testing. More importantly, both of the two component materials, aluminum and Kapton, of the stretched aluminum laminate have long heritage of space applications. However, an inflatable structures rigidized by this method has only very low load-carrying capability. This is due mainly to severe limitations of certain design parameters such as material selection, wall thickness and the degree of post-rigidization straining. To meet the load-carrying requirements of many future applications, a new type of self-rigidizable booms, called the carpenter-tape-reinforced (CRT) aluminum laminate booms, was recently developed at the Jet Propulsion Laboratory (JPL). These booms, sometimes also called the spring-tape-reinforced (STR) aluminum laminate booms, not only have significantly improved buckling capability but also preserve all major advantages of their non-reinforced counterparts. Figure 6 shows an sample CTR aluminum laminate boom. A CTR boom can be easily flattened, rolled-up, and deployed by a relatively low inflation pressure. The buckling capability of the CTR aluminum laminate booms is significantly improved mainly due to the high modulus of elasticity and curved cross-sectional profile of the carpenter tapes. It should also be pointed out that the carpenter tapes are very effective in resisting inward buckling and the aluminum laminate wall is very stable in resisting outward buckling. These two components effectively compliment each other in resisting local crippling of the boom. In addition, unlike the non-reinforced aluminum laminate booms, a CTR aluminum laminate boom relies on the reinforcing tapes, not over-straining induced by high internal pressure, to attain its post-deployment stiffness. The required inflation pressure for a CTR aluminum

laminate boom is relatively low and that, in turn, reduces the load requirements for its seam. Figures 5 shows a sample CTR aluminum laminate boom being tested. Additional development details, including the test results, can be found in [15].

Figure 5. A 5-M CTR Aluminum Laminate
Boom Being Tested

Another on-going research effort at JPL involves the use of space rigidizable foams [16]. JPL, working with Mitsubishi Heavy Industries of Japan, is studying the application of a new type of spaces material, called the Cold Hibernated Elastic Memory (CHEM). CHEM is formulated by incorporating shape memory polymers into open-cellular foam. This material has a maximum deployed/stowed volume ratio of 30 and is self-expanded when heated up above its glass transition temperature. This means that a space rigidizable structure made of CHEM does not need an inflation system to deploy.

5. Modeling and Analysis Capabilities

To successfully apply space inflatable/ rigidizable structures to future missions, analytical tools are needed to effectively model, analyze and simulate in-orbit behavior of this new class of structures. A survey on the state-of-the-art analysis capabilities has recently been conducted [17].

Static Analysis of Inflatable Tubes:

Several earlier papers on static analysis of inflatable tubes can be found in the literature. In 1963, Comer and Levy [18] published a technical note on calculating deflections of an inflated cantilever tube. In 1966, Fichter [19] derived a set of non-linear equations for the bending and twisting of pressurized thin-wall cylindrical beams, based on three important assumptions. The first was that cross sections of the pressurized cylindrical beam remain undeformed under the applied loading. The

second was that cross-sectional translation and rotations are small. The final assumption was that the circumferential strain is negligible. Douglas [20] later investigated the structural stiffness of an inflated cylindrical cantilever beam that is influenced by large deformations. The finite theory of elasticity and the theory of small deformation were employed to obtain explicit analytical results. His analysis also accounts for the changes of geometry and material properties that occur during the inflation process. In the mid-1970's, Steeves [21] used the principle of minimum potential energy to derivea a set of governing differential equations for lateral deformation of inflated beams. A simplifying approximation, assuming that the cross sections of the beam remain undeformed, was then employed to reduce the problem from two dimensions to one dimension. In 1984, Webber [22] proposed a numerical approach to calculate deflections, wrinkling and collapse loads of inflatable beams. He also carried out tests to correlate the analytical results. More recently in 1995, Main et al. [23], in studying bending behavior of an inflated beam, used a two-dimensional Hook's Law to model the stress-strain behavior of the fabric walls.

Dynamic Analysis of Inflating Tubes:

Dynamic analysis of inflation deployment of inflatable tubes has been addressed in several papers published in the 1990s. In 1991, Haung et al. [24] simulated the inflation process of a space inflatable antenna. The explicit finite element code PAM-CRASH that was initially developed to simulate the deployment process of passenger vehicle airbags was employed to perform the simulation. In 1995, Main et al. [25] used the Euler-Bernoulli beam theory to characterize dynamic behavior of inflatable beams. Two damping mechanisms, a viscous damping term and a longitudinal strain damping term, were added. Testing was conducted to obtain the material properties and to correlate the test results with the analysis results. The effect of the gravity was also investigated. In 1996, Rybski, et al. [26] employed the Timoshenko beam theory to calculate the natural frequencies of robotic manipulator, modeled as a cantilevered inflatable beam, and compared the analytical predictions with experimental results. In 1997, Tsoi [27] successfully simulated free inflation deployment of long inflatable tubes. In 1998, Fay and Steele [28], based on the results and observations derived from laboratory experiments,

proposed a constant-curvature model for inflating tubes that are initially either folded or rolled. In 1999, Salama et al. [29] developed an approach that combines finite-volume and finite-element modeling. The gas flowing into an inflating tube was discretized into finite volumes that permit a tractable computation of the instantaneous pressure as function of time. The tube walls were treated as thin-wall shells, either analytically in closed form or by standard finite element modeling technique. This approach was employed to simulate inflation deployment of cylindrical tubes from both Z-folding and from rolled state, and is now being extended to inflatable structures of more complex geometry.

Analysis of Wrinkled Membranes:

The forming of wrinkles in thin-film membranes and analyses of wrinkled membranes have been previously addressed by many researchers. In 1961, Stein and Hedgepeth [30] first presented a theory to predict the stresses and deformations for partly wrinkled membranes. In 1964, Mikulas [31] analyzed the wrinkling behavior of a stretched membrane subjected to torsion loading through an attached hub. In 1982, Miller and Hedgepeth [32] developed a numerical algorithm that retains the simplicity of form characteristic of linear elastic case, but is consistent with the nonlinear Stein-Hedgepeth wrinkle model. An equivalent elasticity matrix was defined to relate the stresses and elastic strains and this matrix was used to determine whether a membrane element is in the slack, taut, or wrinkled status. In 1991, Jenkins and Leonard [33] published a review paper on nonlinear analysis of membrane structures, focusing on the formulation of field equations, wrinkling analysis, fluid/structure interactions, material nonlinearities, and computational schemes. In 1993, Li and Steigmann [34] used a direct theory of elastic membranes to analyze the finite deformation of an annular membrane induced by the rotation of a rigid hub. Also in 1993, Gorman and Singhal [35] used the Rayleigh-Ritz energy method to develop an analysis technique for obtaining accurate stress distributions in corner-tensioned rectangular membranes. In 1994, Haseganu and Steigmann [36] used the dynamic relaxation method to analyze partly wrinkled membranes. In 1996, Lin and Mote [37 and 38] used a modified von Karman's nonlinear plate equations and tensioned Kirchhoff plate equations to analyze stress distributions, wrinkling and stability of axially moving webs. Two criteria predicting wrinkling were established; one

for isotropic, compressible rectangular webs under uniform in-plane principal stresses and the other for isotropic, incompressible membranes. In 1997, Kang and Im [39] proposed a scheme for finite element analysis of wrinkling and applied it to analyze both anisotropic and isotropic membranes. In 1998, Kissel [40] employed the IMOS computer code to model the NGST sunshield with wrinkled membranes. A parallel MSC/NASTRAN dynamic analysis on the same sunshield was performed by Fang and Lou [18]. In 1999, Lenard [41], using a cable network approximation, conducted UAI/NASTRAN dynamic analyses of the ISIS sunshield with multiple layers of wrinkled thin-film membranes. His analysis results were correlated with scale-model testing in a vacuum chamber. Currently, research efforts are continuing to develop more effective methods for modeling and analyzing wrinkling and dynamics of wrinkled membranes [e.g., 42 and 43].

Next-Generation Analysis Tools:

At present, commercially available finite element modeling codes are commonly used to analyze low-precision space inflatable structures. The application of these codes is subjected to several limitations. First, because there are stringent requirements for the aspect ratios of finite elements, it requires tens of thousands of elements just to model a single long tube. As a result, conventional finite-element structural analysis of inflatable structural systems becomes extremely time-consuming and computational inefficient. Second, for low-precision applications, the inflatable structures are commonly used to support large, pre-stressed membranes. The structural behaviors of these membranes are governed by differential stiffness derived from the pre-stresses. The commercially available finite-element analysis codes such as NASTRAN and ANSYS, however, do not automatically include such differential stiffness. Therefore, analysis accuracy will be excessively dependent of the user's experience and judgement. Third, the deployment dynamics of an inflating structural system is extremely complicated, influencing by factors such as structural flexibility, time-varying differential stiffness, large deformations, material nonlinearity, and interaction of structural and aerodynamic forces. It is beyond the capability of currently available finite-element computer codes to accurately address the combined effects of all these factors.

Next-generation analysis capabilities and tools developed specifically for space inflatable structures are urgently needed. One of the recently initiated research efforts in meeting this need involves the use of the Strip Distributed Transfer Function Method (SDTFM) [44 and 45]. The SDTFM discretizes a structural element, such as a long inflatable tube, into a finite number of strips and solves the governing equations of the strips by first transforming them from time domain into Laplace domain. This reduces the orders of the mass and stiffness matrices and improves computational efficiency and accuracy. The SDTFM is most suitable for analyzing complex and highly nonlinear structural systems that consist of long tubes. Figure 6 shows typical results obtained form a recently conducted SDTFM analysis on bucking of an inflatable tube [46].
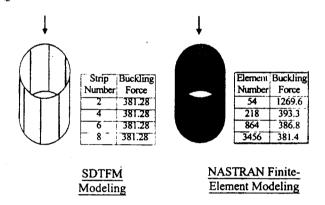

Strip Number	Buckling Force
2	381.28
4	381.28
6	381.28
8	381.28

SDTFM
Modeling

Element Number	Buckling Force
54	1269.6
218	393.3
864	386.8
3456	381.4

NASTRAN Finite-
Element Modeling

Figure 6. SDTFM vs. Finite-Element Modeling

6. Material Characterization and Space Survivability

Space inflatable/rigidizable structures form a class of relatively new space structures. Many materials used in manufacturing these structures have no previous space heritage and, in some cases, have not yet fully characterized for space applications. This has made the material selection in designing space structures very difficult and comprehensive materials databases are urgently needed. The development of the needed material databases should follow uniform test requirements and data formats that are widely accepted by the researchers in government agencies, industry companies and academic researchers. The databases should also include, as a minimum for each material, basic mechanical properties such as mass density, tensile strength and modulus, yield strength and elongation, and coefficient of thermal expansion. In

addition, because polymers and polyamide films are widely used in fabricating space inflatables, it is important to assess the long-term space survivability of these materials. The effects of space environments, including extreme hot and cold temperatures, vacuum, atomic oxygen, radiation, and electrostatic charges, meteoroids and space debris, must be quantified. It is unfortunate that most of the materials data developed by industry companies are kept proprietary and only very limited amount of information are available in the public domain [47 and 48].

7. Future Development and Applications

In the next few years, space inflatable structures technology will continue to advance at a fast pace. However, infusion of this technology to future missions can be achieved only when all of its fundamental technology elements, including deployment control and stability, space rigidization, modeling and analysis capabilities, material characterization and long-term space survivability, are fully developed and space validated.

Many technology development and application roadmaps have recently been proposed for large lightweight space structures, including space inflatables. Figure 7 shows one of the roadmaps that were specifically prepared for low-precision applications. It can be seen that the near-term applications of inflatable structures concentrate on sunshields, radar antennas and solar arrays. Beyond that, the mid-term and long-term applications will focus on solar sails and human habitats in space. Solar sails provide one the most efficient means of space transportation for many future missions - from non-Keplerian orbits to interstellar probes that will reach and explore the edge of our solar system. Space inflatable/ rigidizable structures are being considered for large sails of sizes up to 100 meters and with areal densities less than 10 grams/m^2. Currently, NASA is also studying the feasibility of employing space inflatables in human exploration missions.

Large Lightweight Space Structures
Low-Precision Applications

- Simple inflatable structures
- Off-the-shelf materials
- Scaling laws and ground test methods
- Experimental rigidization

Enables simple structures of up to about 50 m

- Space Demo and Tech Validation
  - ST-5, ISIS , ISAE

- Long-term (> 3 years) space survivability
- Space-durable materials
- Space-validated rigidization
- Space-validated analysis and simulation capabilities

Enables 100-m planar structures and solar sails

- GeoStorm Warning
- NGST Sunshade
- Lightweight, Low-Cost SAR Missions
- S/A and S/S for ESS Missions

- Survivability in extreme space environments
- Adaptive structures
- $\leq 1\mu$ -thick thin films
- ≤ 5 g/m^2 solar sails

Enables adaptive optics and 800-m solar sails

- Outer Planet Missions
- Interstellar Missions

- In-orbit configuration change and expansion
- Self-monitoring and self-reparable
- Space-based fabrication & assembly

Enables expandable space structural systems

- Interstellar Missions
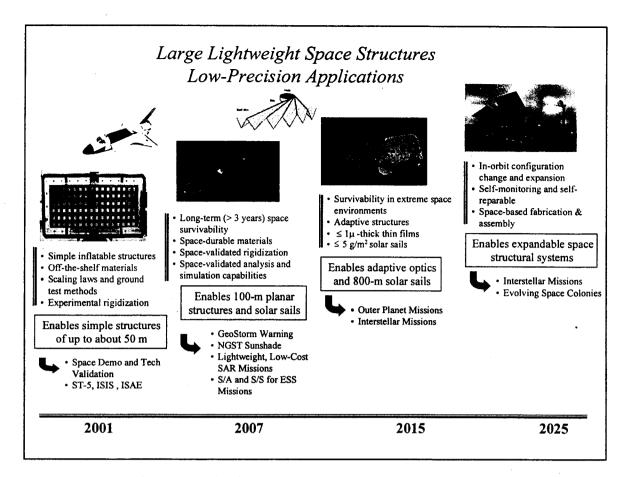- Evolving Space Colonies

| 2001 | 2007 | 2015 | 2025 |

Figure 7. Technology Development and Application Roadmap

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